Progress of development of ultra-high timing TOF for SoLID

Yancheng Yu

Department of Engineering Physics, Tsinghua University

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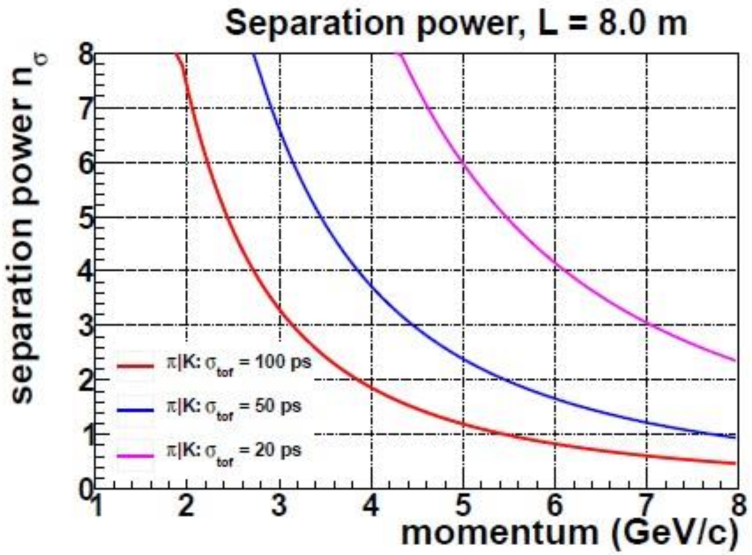
Outline

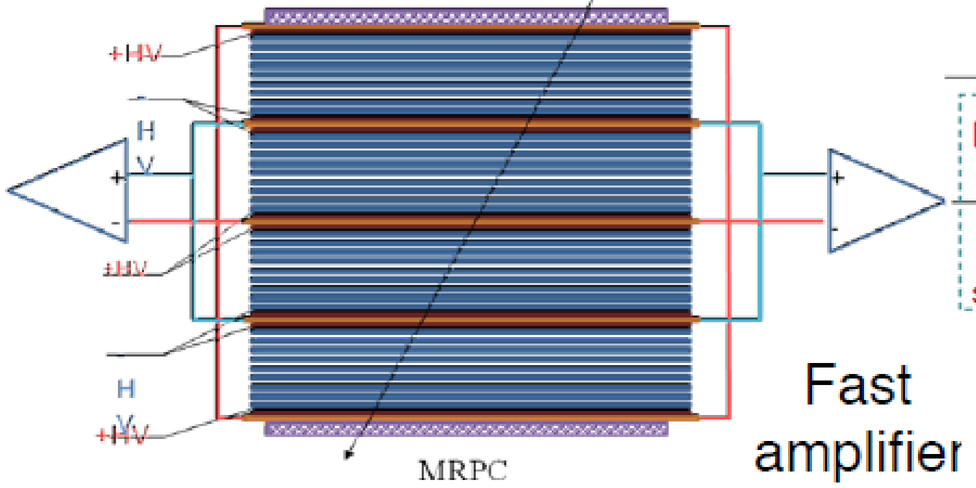
- **R&D of the Next-Gen MRPC**
  - Cosmic test setup
  - Preliminary results
- **The impedance of transmission lines in MRPC Detector**
  - Impedance test
  - Approximate formula for estimation
  - Machine learning approaches--SVR
- **Summary**

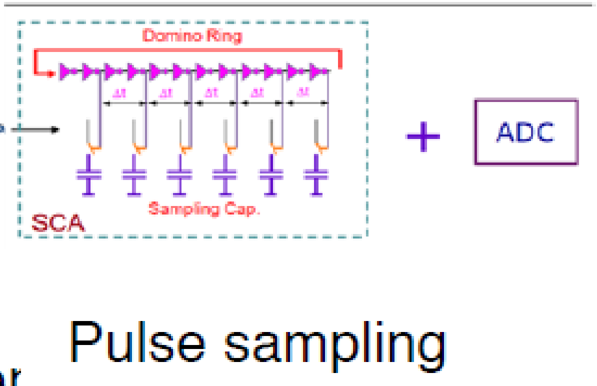
Part Ⅰ
R&D of the Next-Gen MRPC

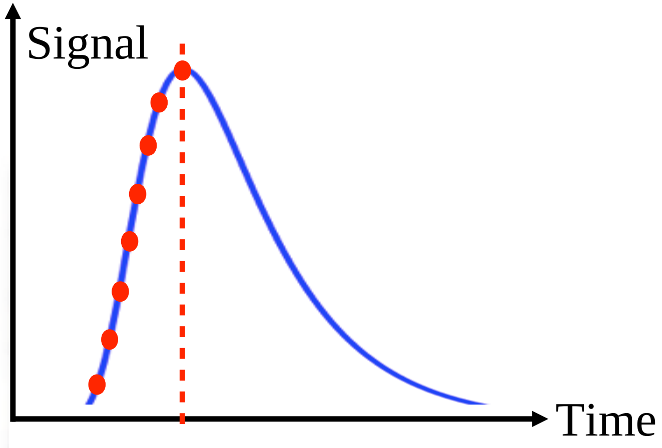
Introduction

- Multi-gap Resistive Plate Chamber (MRPC) has been widely used for time of flight (TOF) systems for particle identification, particularly in high-energy physics.
- In SoLID experiment, the requirements for the TOF system are:
  - ✓ pi/k separation up to 7GeV/c
  - ✓ Time resolution < **20ps**
  - ✓ Rate capability > **10kHz/cm2**
- The next generation MRPC is proposed by Tsinghua collaboration
- The electronics: fast amplifier and wave form digitizer system

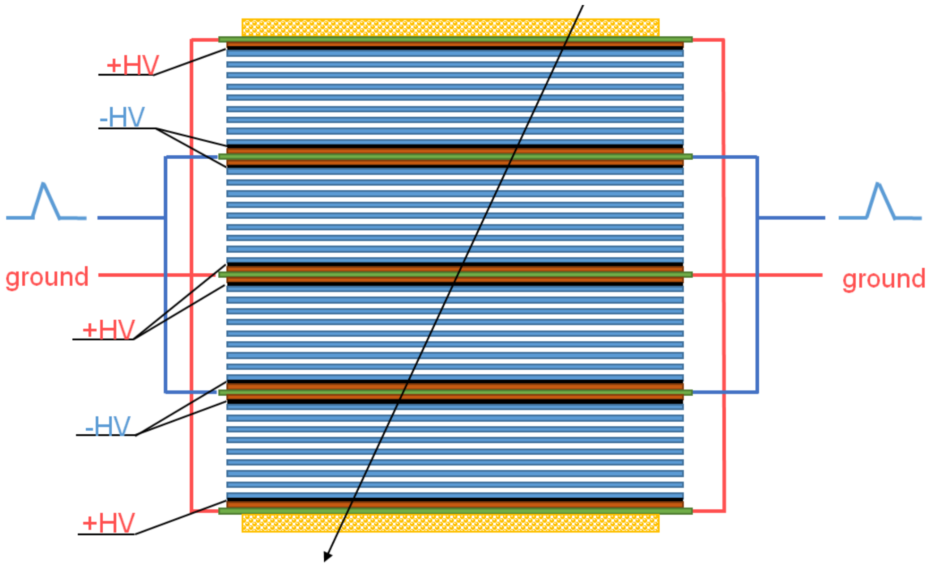








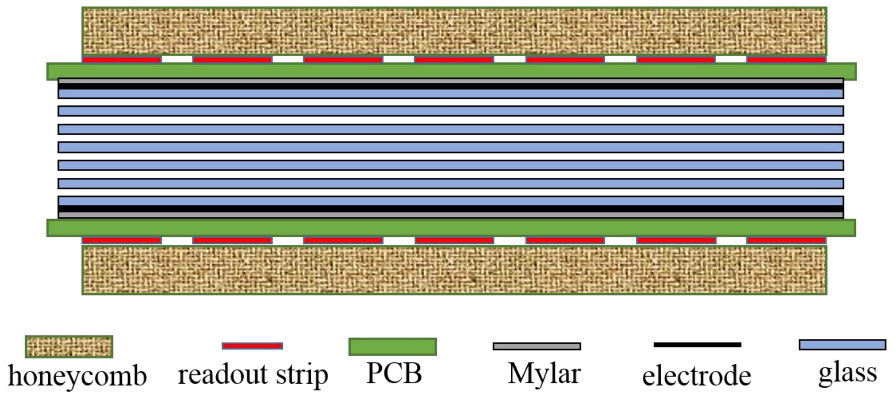
Introduction



Tsinghua Prototype, 2016
Gas gap width: 104um
Number of gas gap: 32

- **Narrower gap width** →fast charge dominant in the induced signal → Better timing resolution
- **More gas gaps** → Efficiency will be recovered

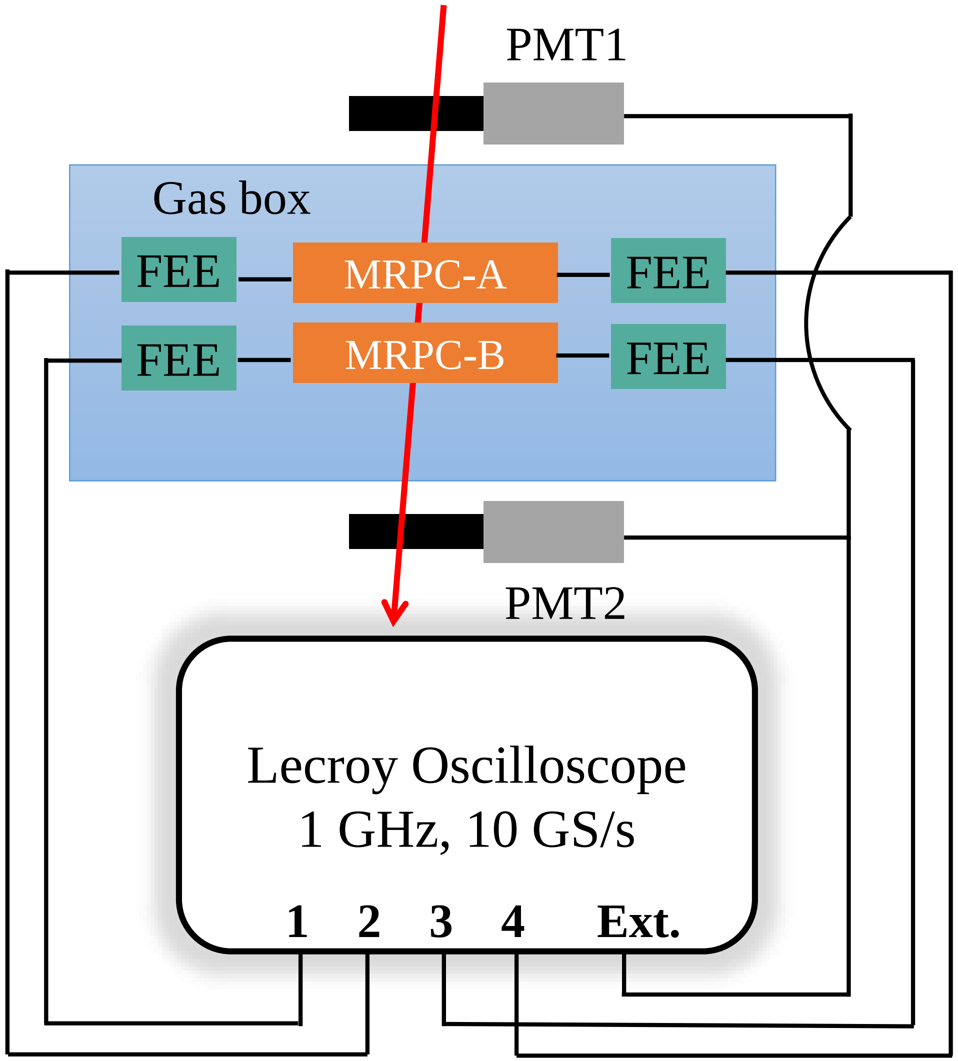
Tsinghua Prototype, 2018

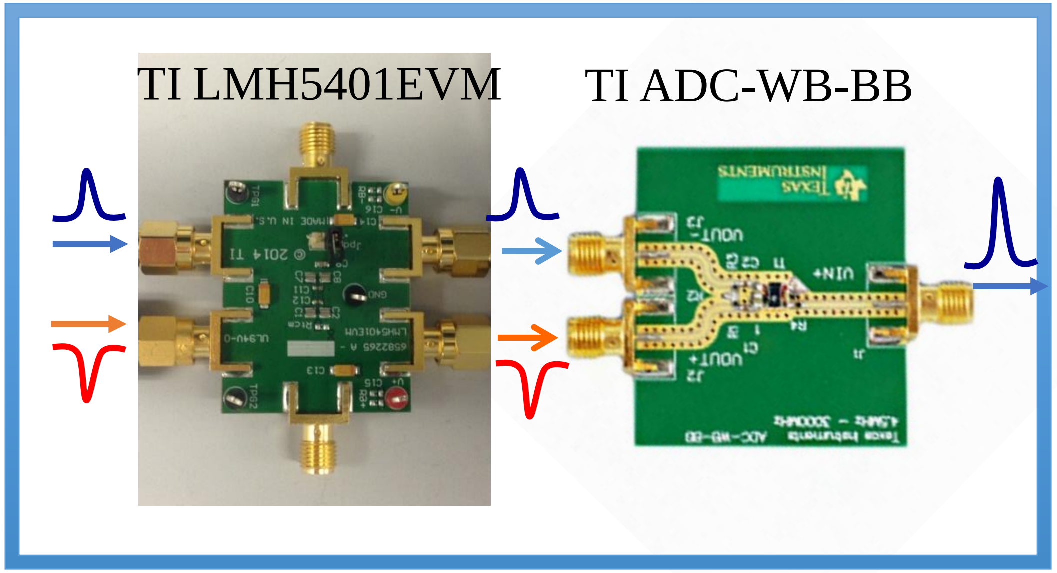


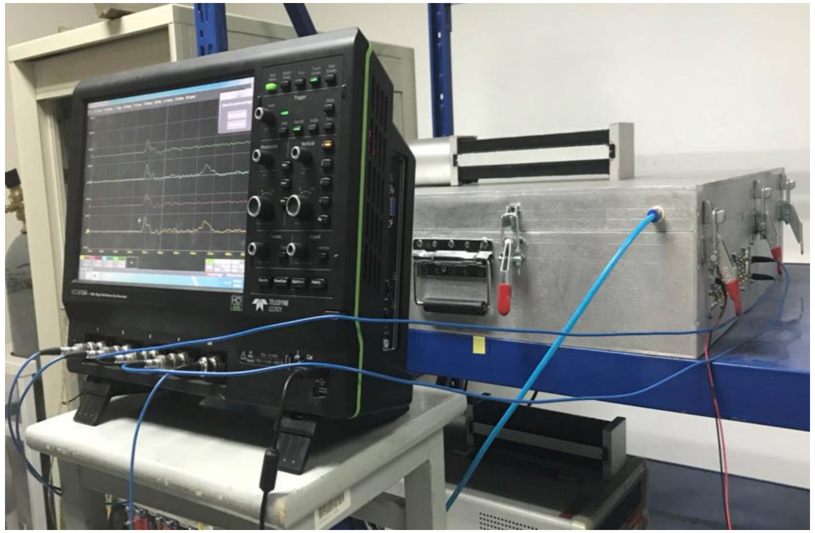
	Single-stack MRPC
Gas Gap Width	250 um (fishing line)
Number of Gas Gaps	1 stack x 6 layers = 6
Float Glass Thickness	700 um
Readout strip	7 mm x 270mm(3 mm internal)
Readout	differential, both ends

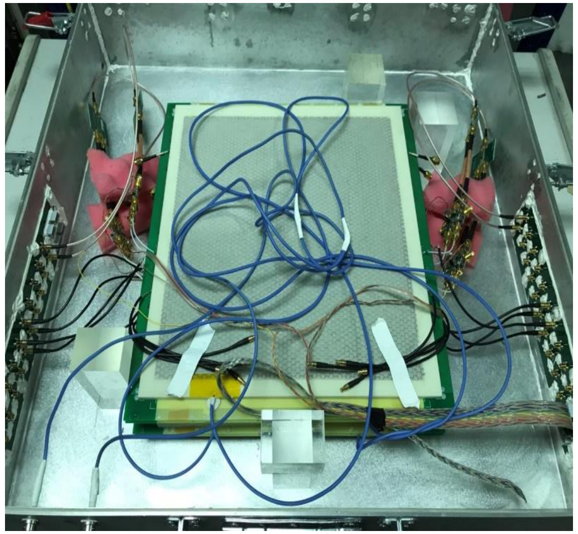
Cosmic test setup

Gas component: **90% $C_2H_2F_4$ + 5% i-C_4H_{10} + 5% SF_6**

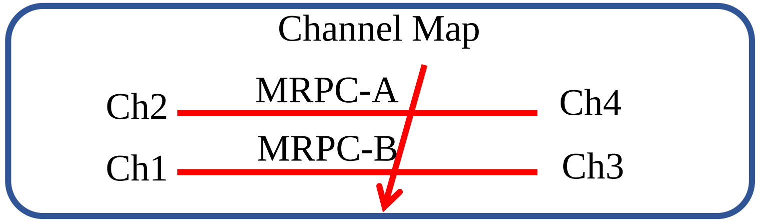


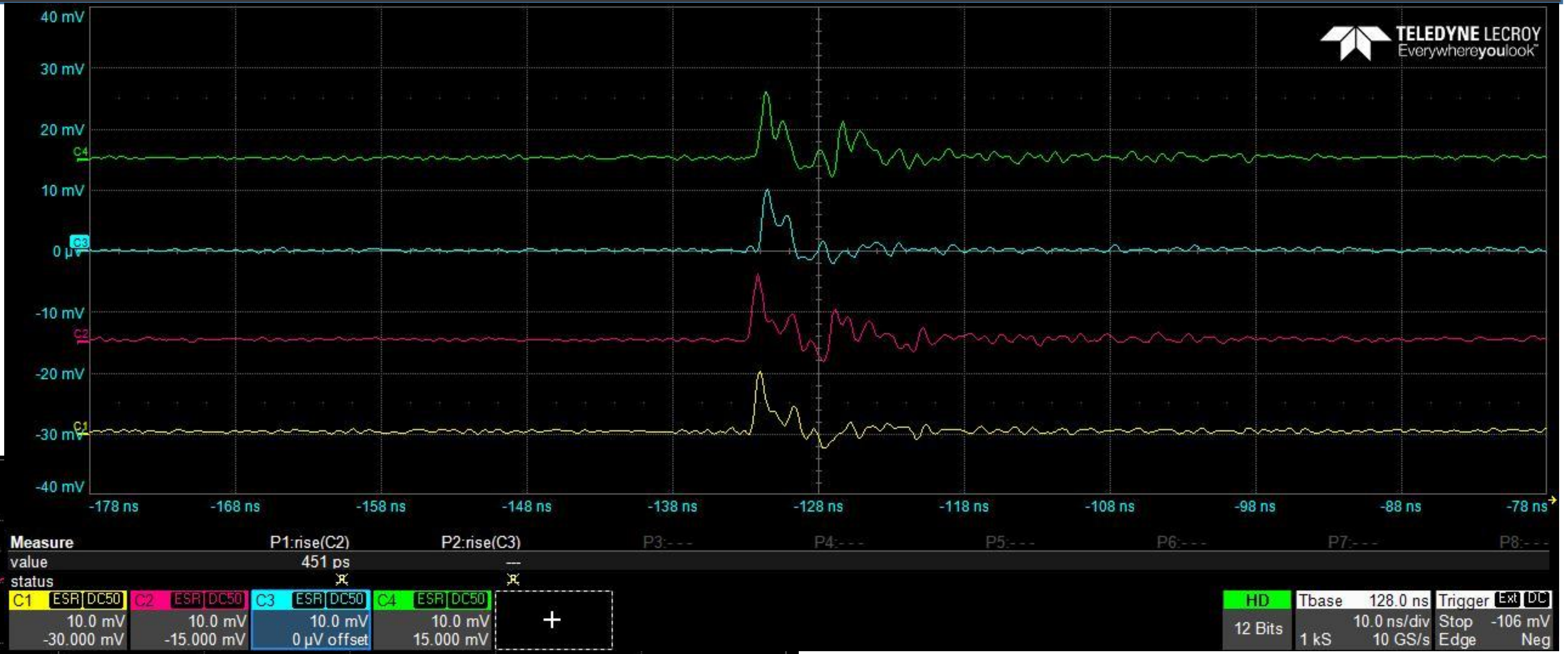






Signal observation



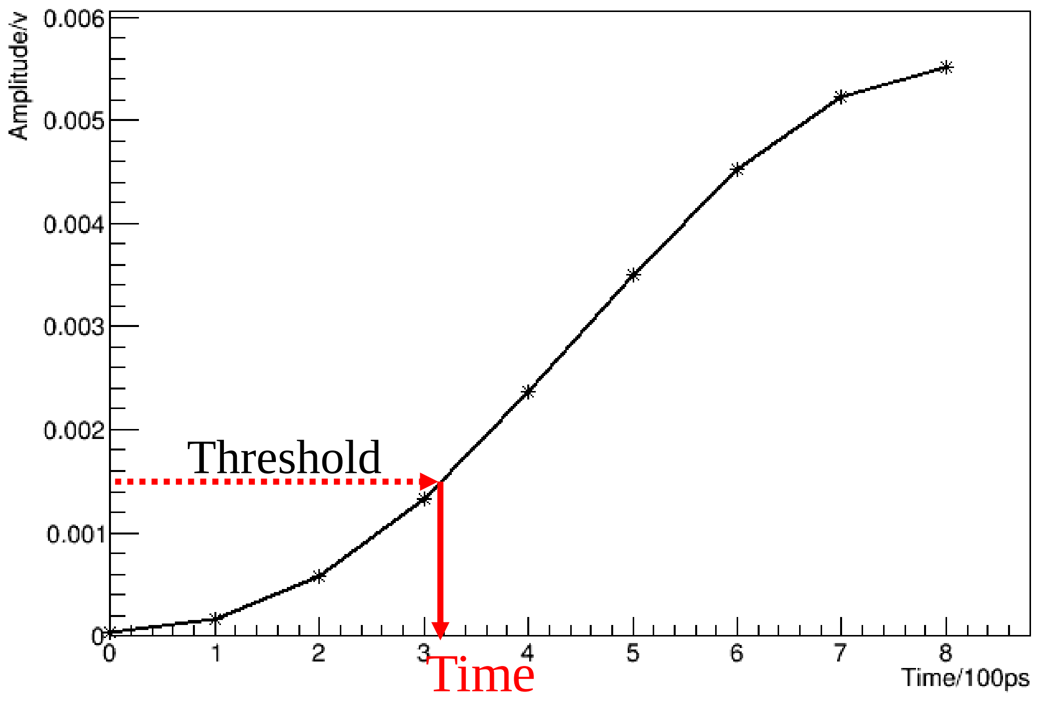


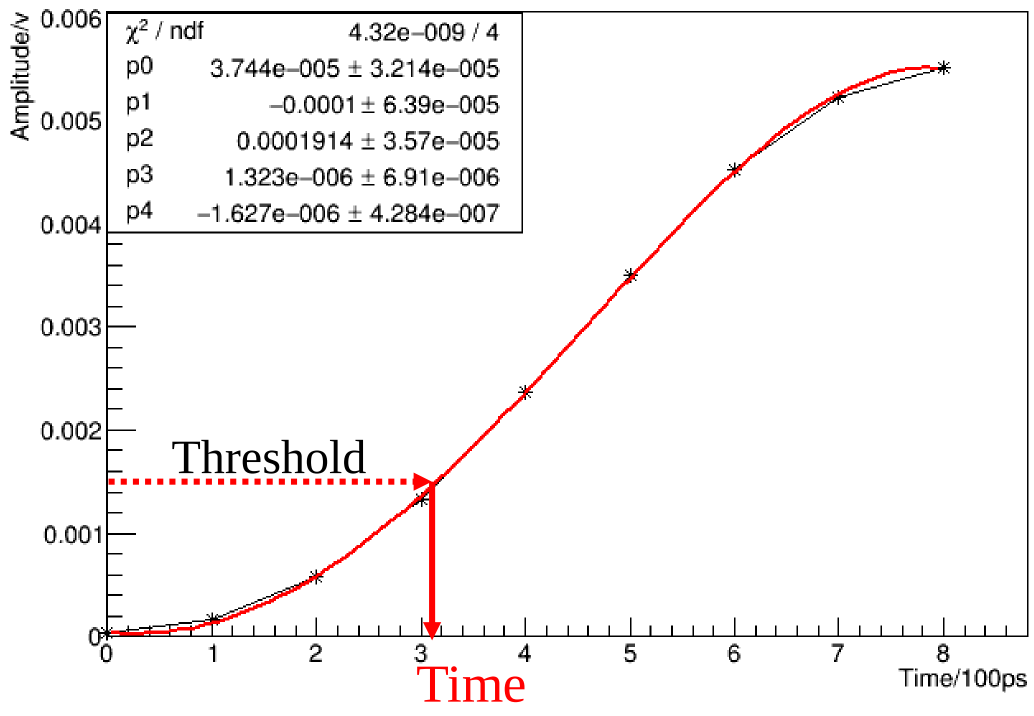
High voltage: 16.5KV
Sampling interval ~ 100ps
Pedestal σ < 0.15mV
Rise time ~ 450ps

Timing method

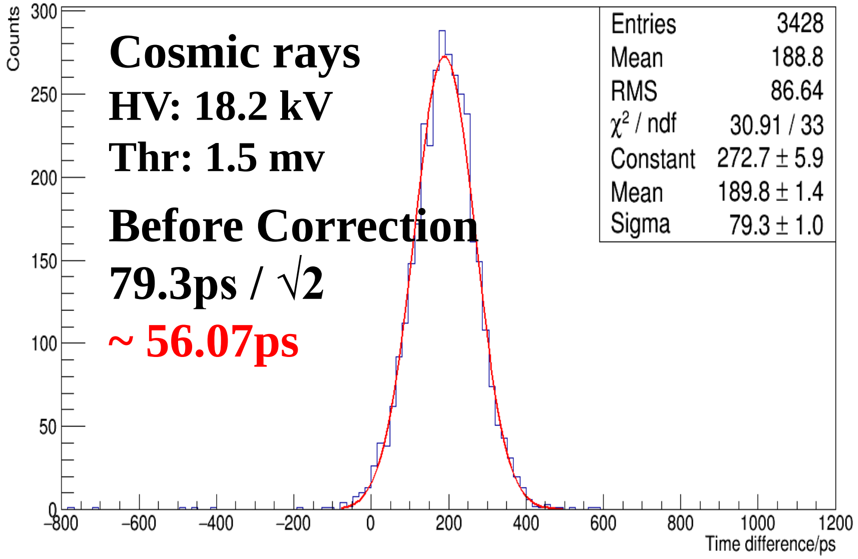
Algorithm to find a ref. time T (Fixed threshold)

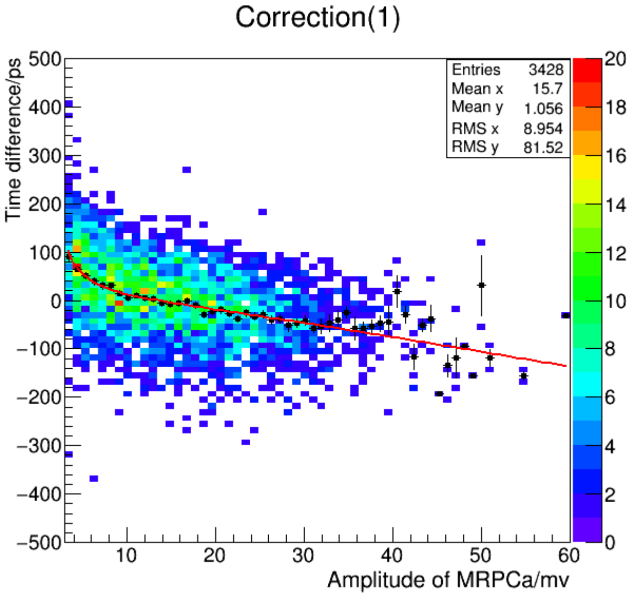
- Linear interpolation
- Polynomial fit

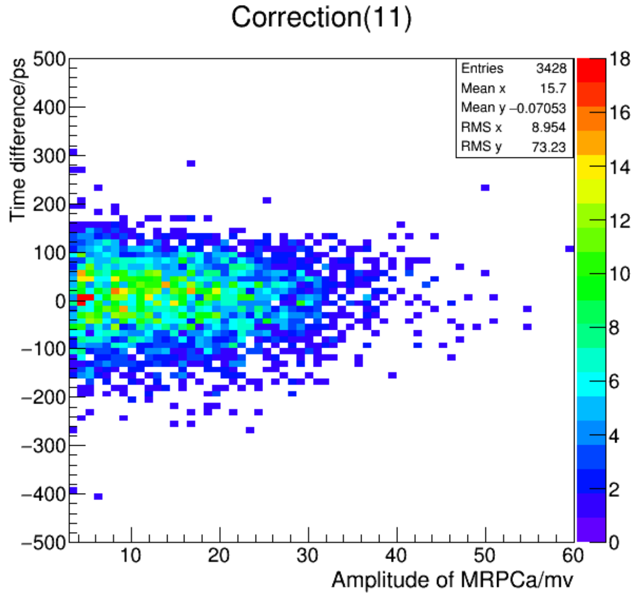


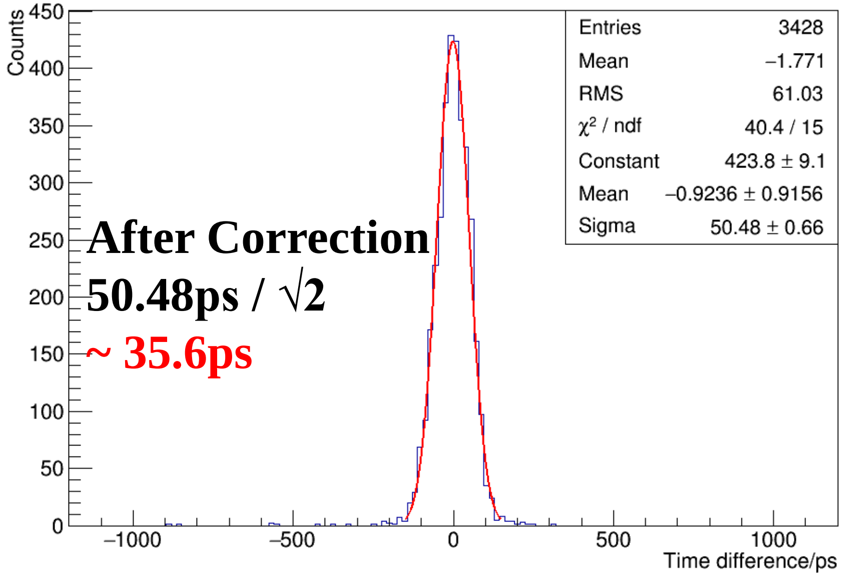


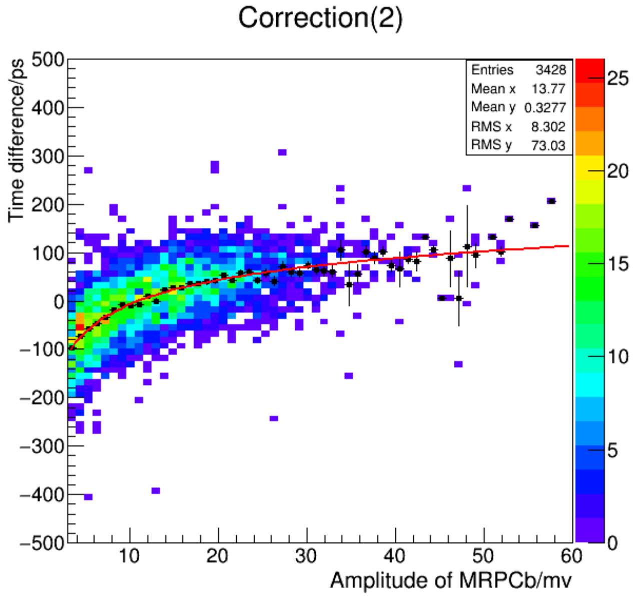
Time Resolution----Linear Interpolation

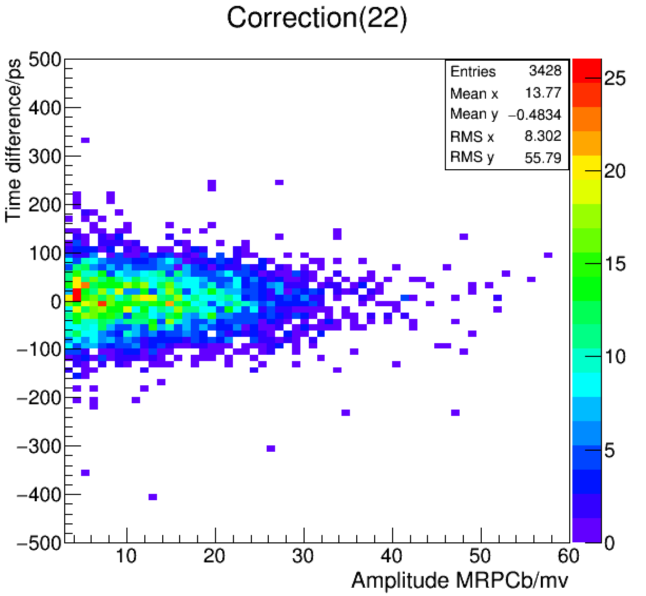




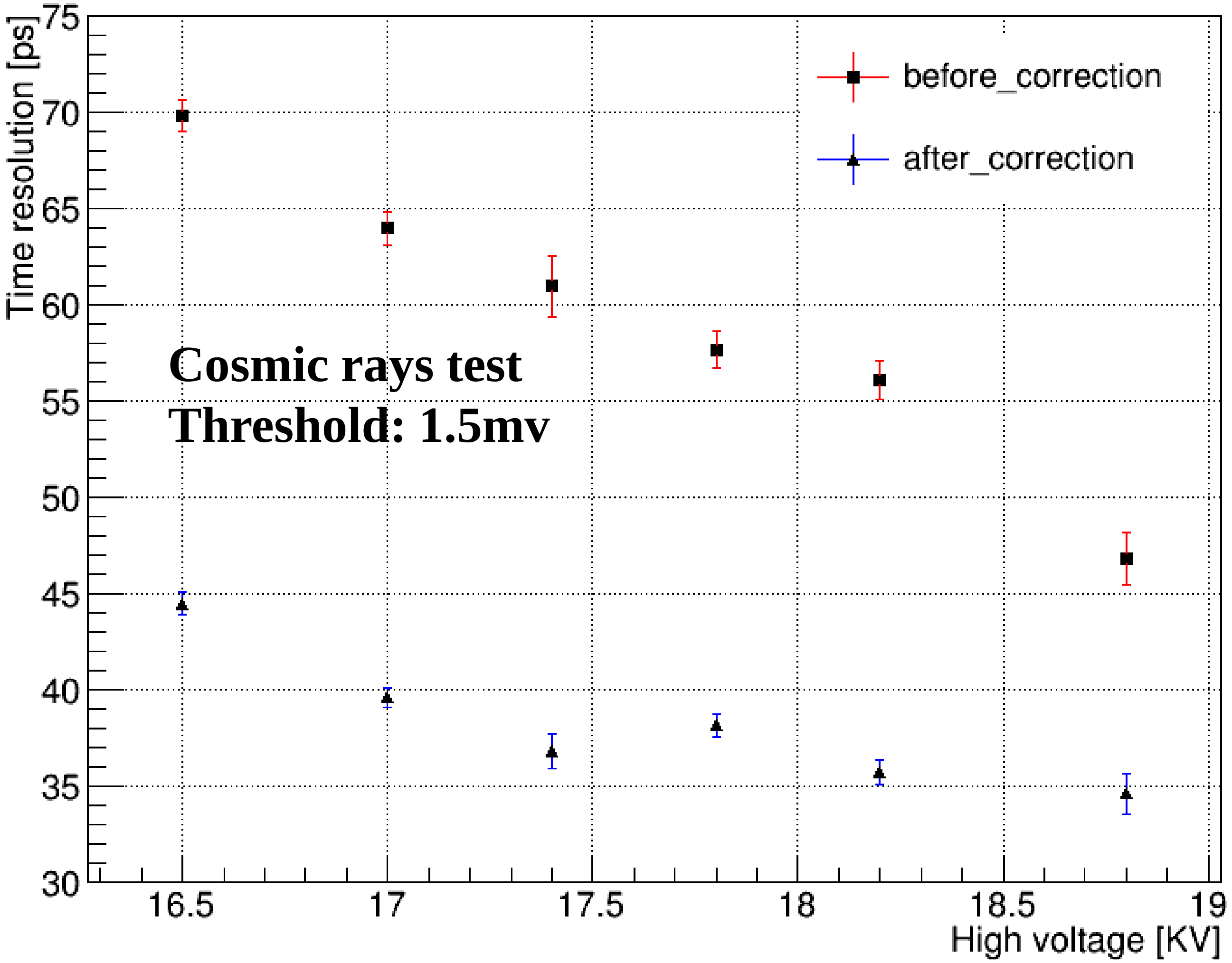






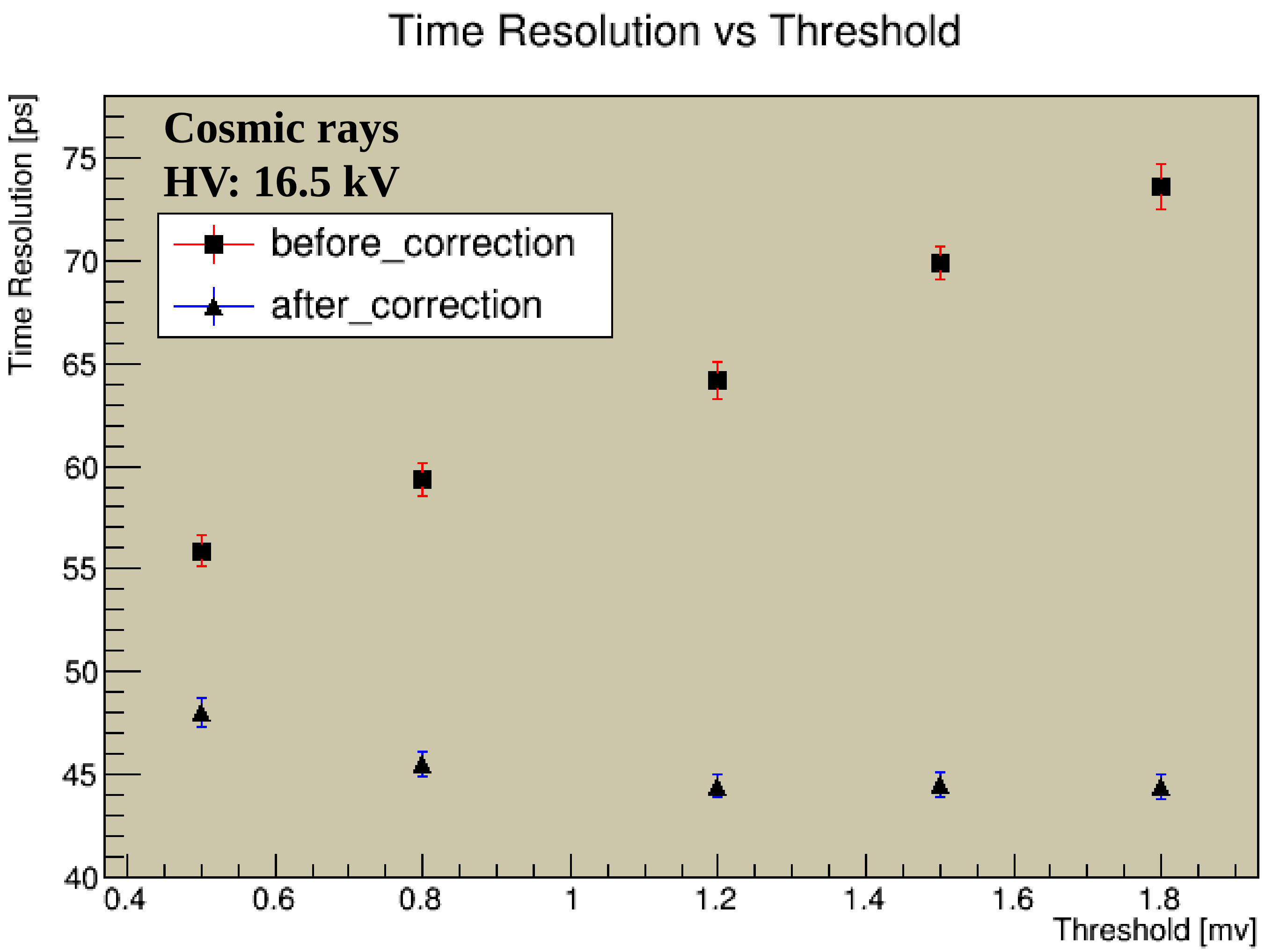


Time Resolution vs HV



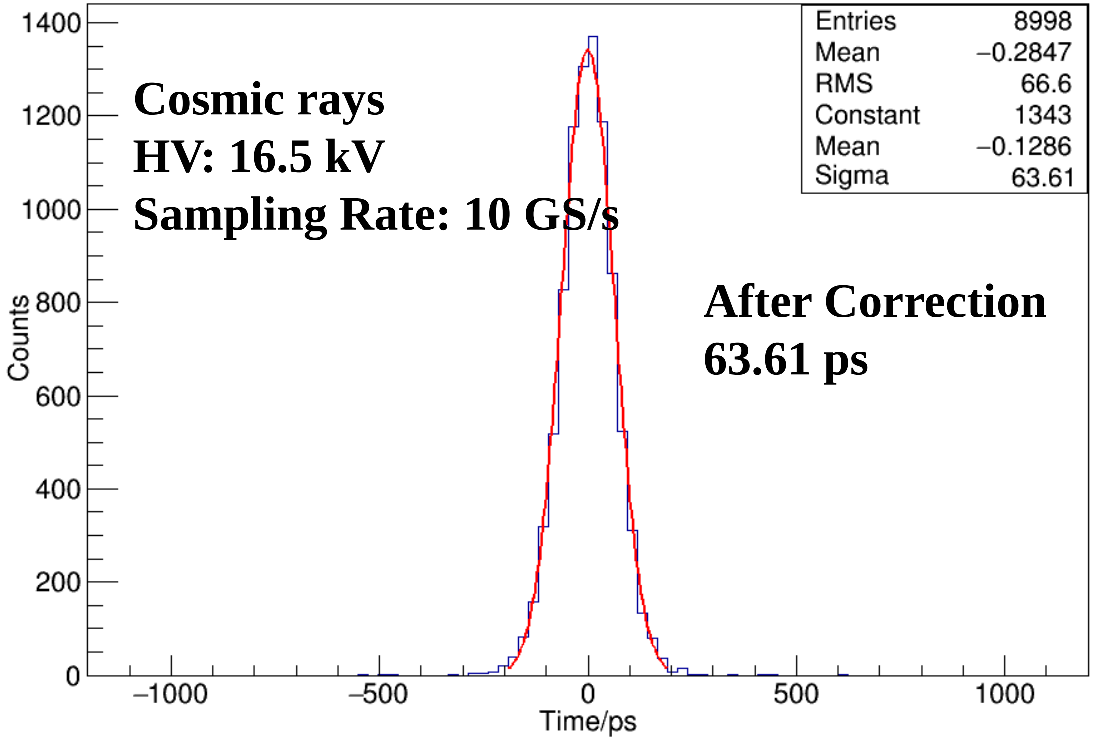
✓ Higher working HV to achieve better time resolution.

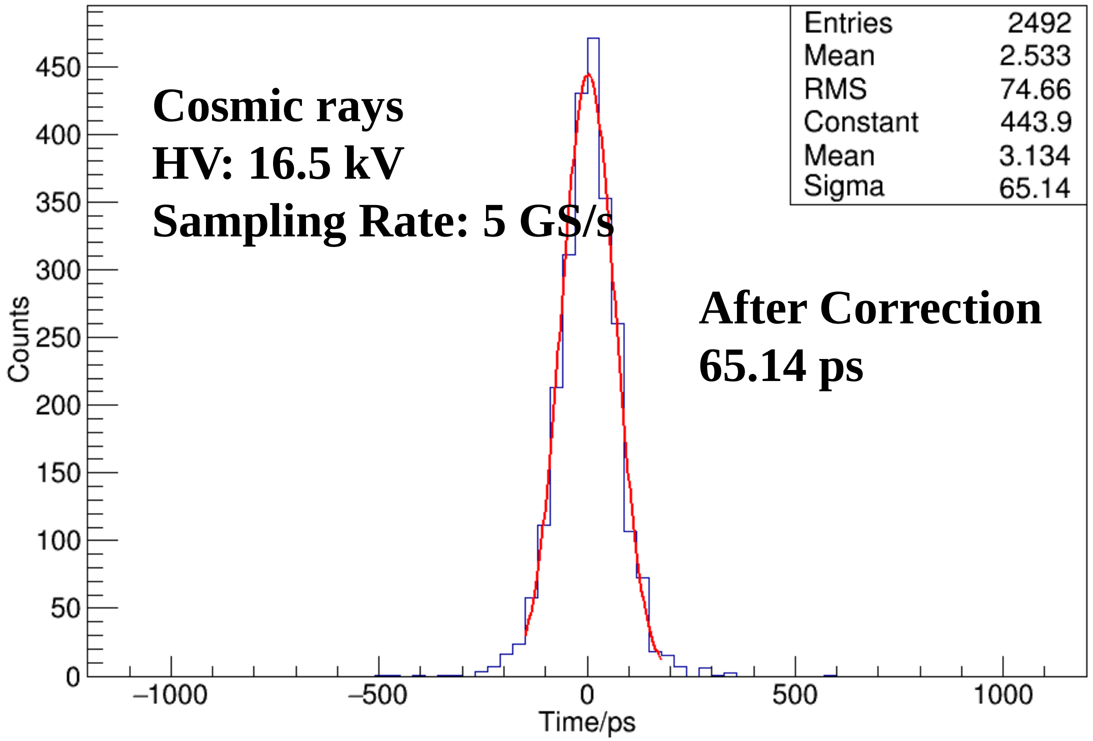
Time Resolution vs Threshold



- ✓ Time-slewing effect is more obvious when increasing the threshold.
- ✓ The time resolution after slewing correction is almost the same at different threshold.

Time Resolution vs Sampling Rate





- ✓ For waveform digitizer based on DRS4, Sampling rate: ~ 5 GS/s
- ✓ Shannon sampling theory: f >2 B

Next

Next…

- ☐ Test of 4 strips at least (needs 16 channels)
- ☐ Test the 32-gaps MRPC (gas gap width~104μm)
- ☐ Develop high-rate MRPC with the low resistive glass
- ☐ Beam test

…

Part Ⅱ
Study on the impedance of transmission lines in MRPC Detector

The impedance test

- **Impedance matching** of the signal transmission line to the input impedance of the front-end electronics is very critical.
- The impedance test platform based on Digital Sampling Oscilloscope (DSA8300) has been set up.
- It allows for differential or common mode **TDR or S-parameter** testing of two coupled lines.

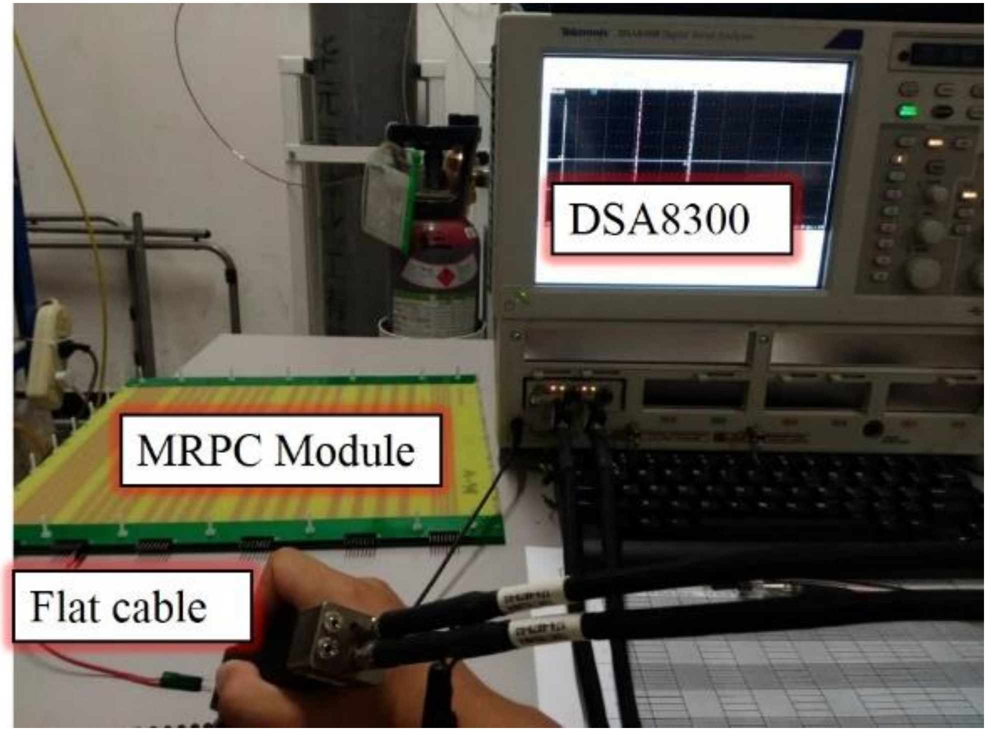
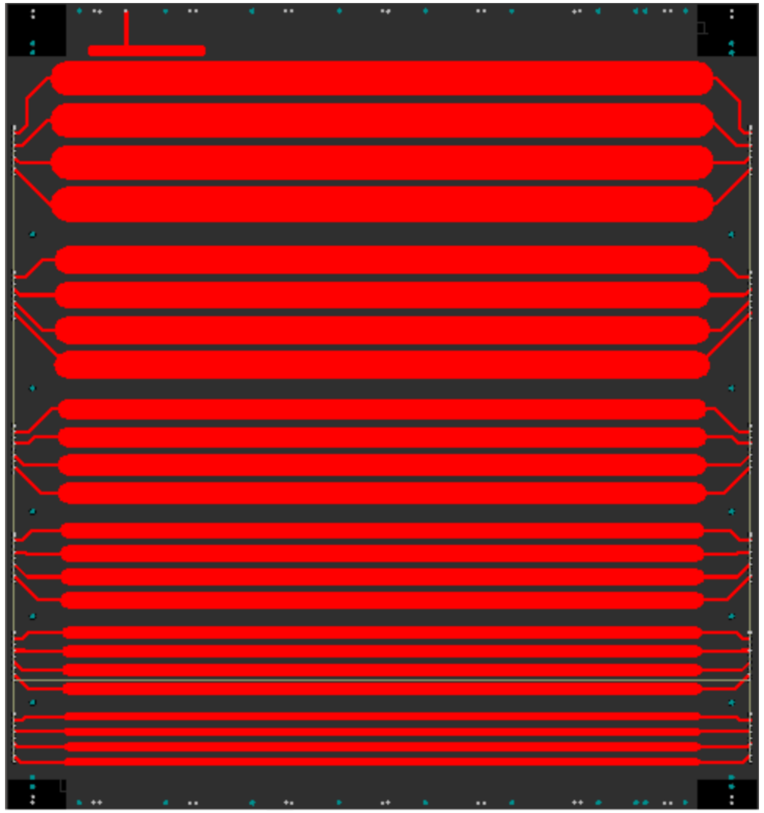


Figure 1 Impedance Test Platform

Figure 2 Differential TDR Waveforms

The impedance test



Readout strips with different width

MRPC parameters:

- Different width of strips: 3.5, 5, 7, 9, 12, 15(mm)
- The number of gas gaps: 4, 6, 8
- The number of stacks: 1, 2, 3, 4
- The thickness of gas gaps: 0.12, 0.20, 0.28(mm)

  ----Determined by fishing line
- The thickness of **the float glass**: 0.23, 0.7 (mm)

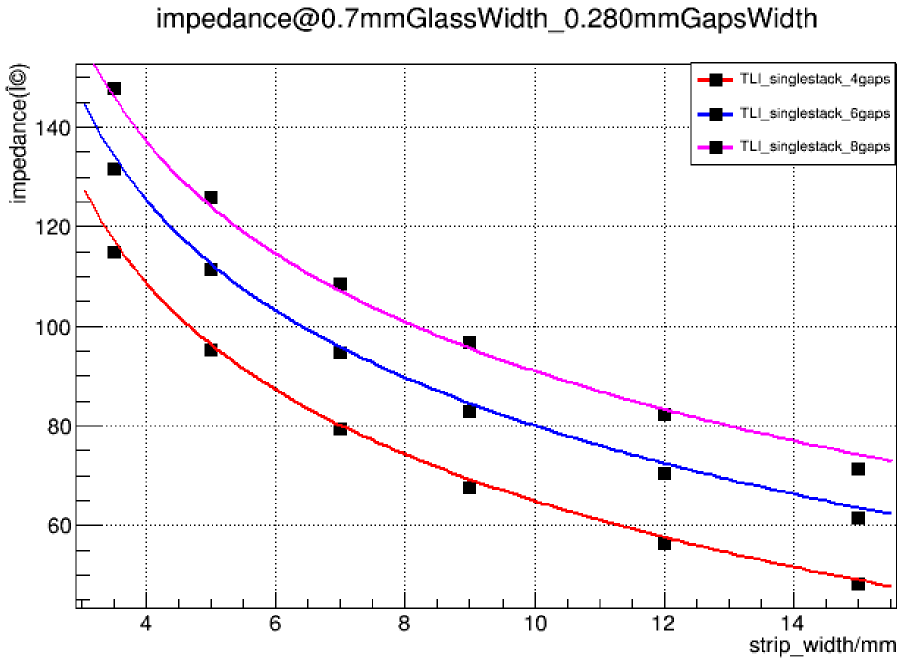
➢ **72** kinds of MRPC detectors have been finished and tested

➢ **432** sets of impedance data

Approximate formula for impedance estimation

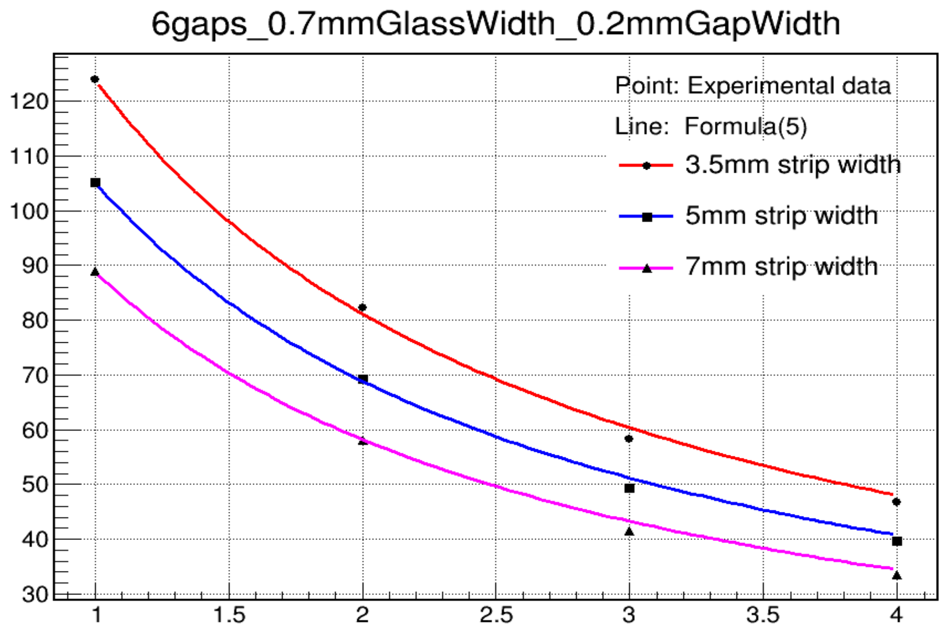
Goal:

- ☐ Study on the relationship between the impedance and the width of strip, the thickness of gaps……
- ☐ Develop an approximate formula for impedance estimation



Impedance Results of three single-stack MRPCs

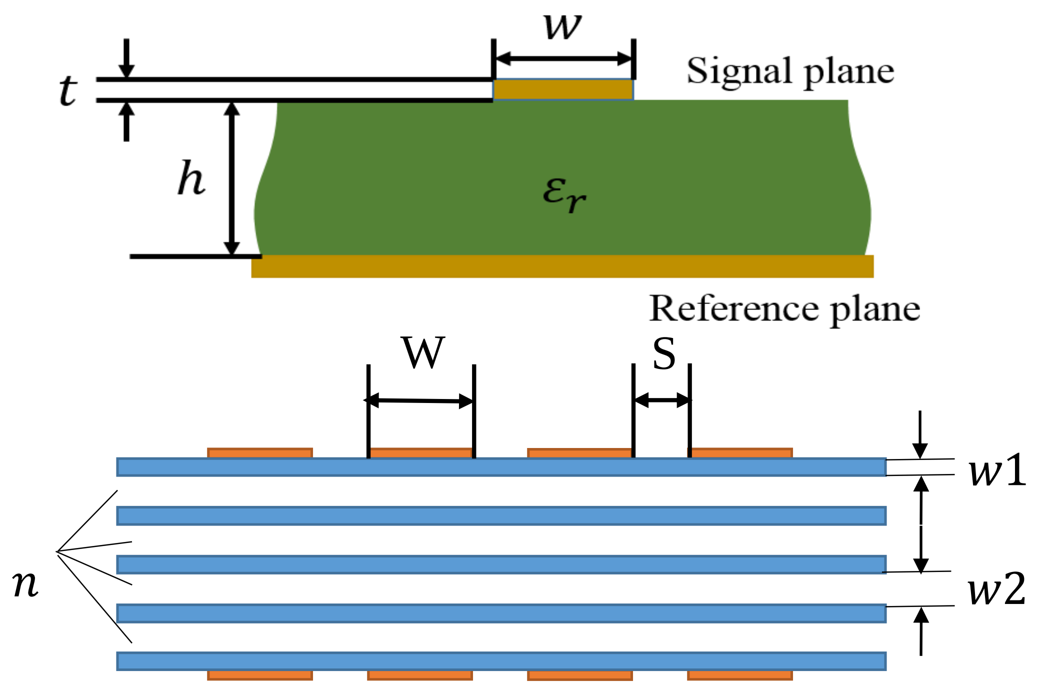
$$Z \propto \log \frac{a}{\color{red}{widthofstrip} + b}$$



Impedance Results of MRPC modules with different stacks

$$Z_{0,ns} = \frac{(1+0.895) \times \color{red}{Z_{0,single-stack}}}{\color{red}{ns} + 0.895}$$

Approximate formula for impedance estimation



$$Z_0 = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln \frac{5.98h}{0.8w + t}$$

Coefficients: $a(1) - a(8)$
Number of gas gaps: n
Number of stacks: ns
Width of glass: w1
Width of gaps: w2
Width of strips: w
Equivalent dielectric constant: ε

Approximate formula for impedance estimation in MRPC detector:

$$Imp = \frac{\frac{a(1)}{\sqrt{\varepsilon + a(2)}} \times \log \frac{a(3) \times n \times w2 + a(4) \times (n+1) \times w1}{w - a(5)} + a(6) \times \sqrt{\frac{w}{n \times w2 + (n+1) \times w1}} + a(7) \times \log \frac{w1}{w2}}{ns + a(8)}$$

$$\varepsilon_{eq} = \left(\frac{n \times w2 \times \sqrt{\varepsilon_{air}} + (n+1) \times w1 \times \sqrt{\varepsilon_g}}{n \times w2 + (n+1) \times w1} \right)^2$$

Approximate formula for impedance estimation

Approximate formula for calculating the impedance of transmission lines in MRPC Detector:

$$Imp = \frac{\frac{a(1)}{\sqrt{\varepsilon + a(2)}} \times \log\frac{a(3)\times n \times w2 + a(4)\times(n+1)\times w1}{w - a(5)} + a(6)\times\sqrt{\frac{w}{n\times w2 + (n+1)\times w1}} + a(7)\times\log\frac{w1}{w2}}{ns + a(8)}$$

Coefficients: $a(1) - a(8)$

406.3467 ± 15.0495

8.6294 ± 1.0010

6.1138 ± 0.1998

0.6871 ± 0.0606

0.5577 ± 0.0289

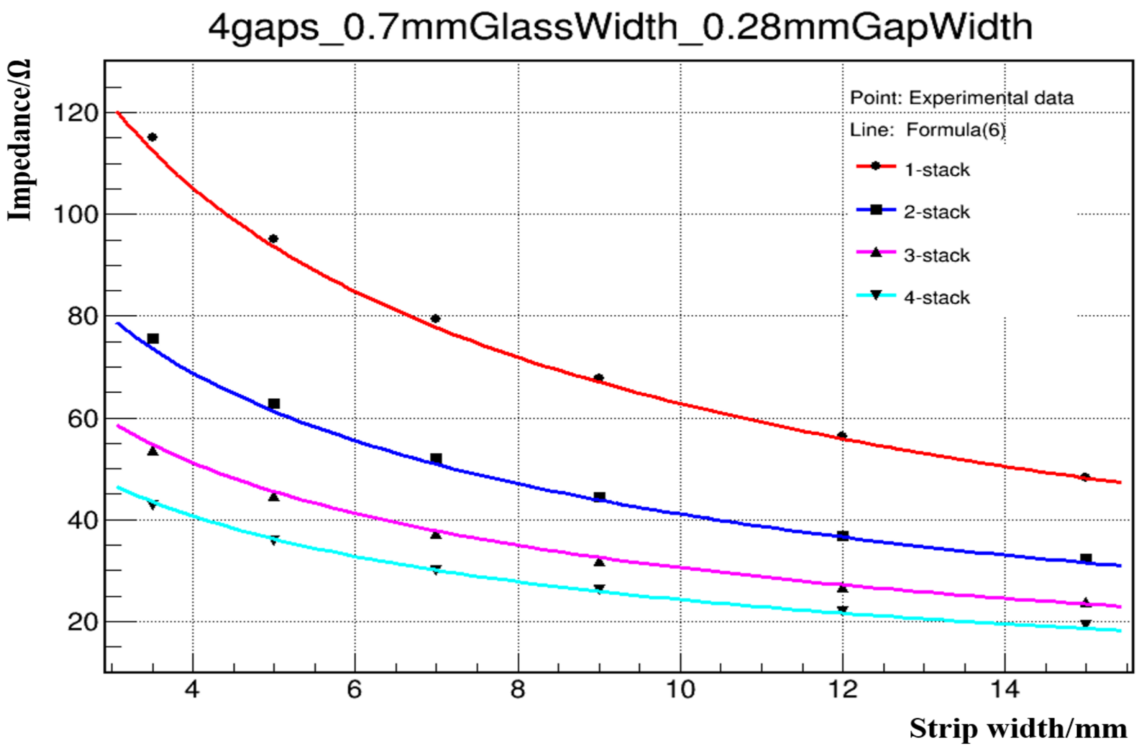
59.0823 ± 1.8964

37.5319 ± 1.8673

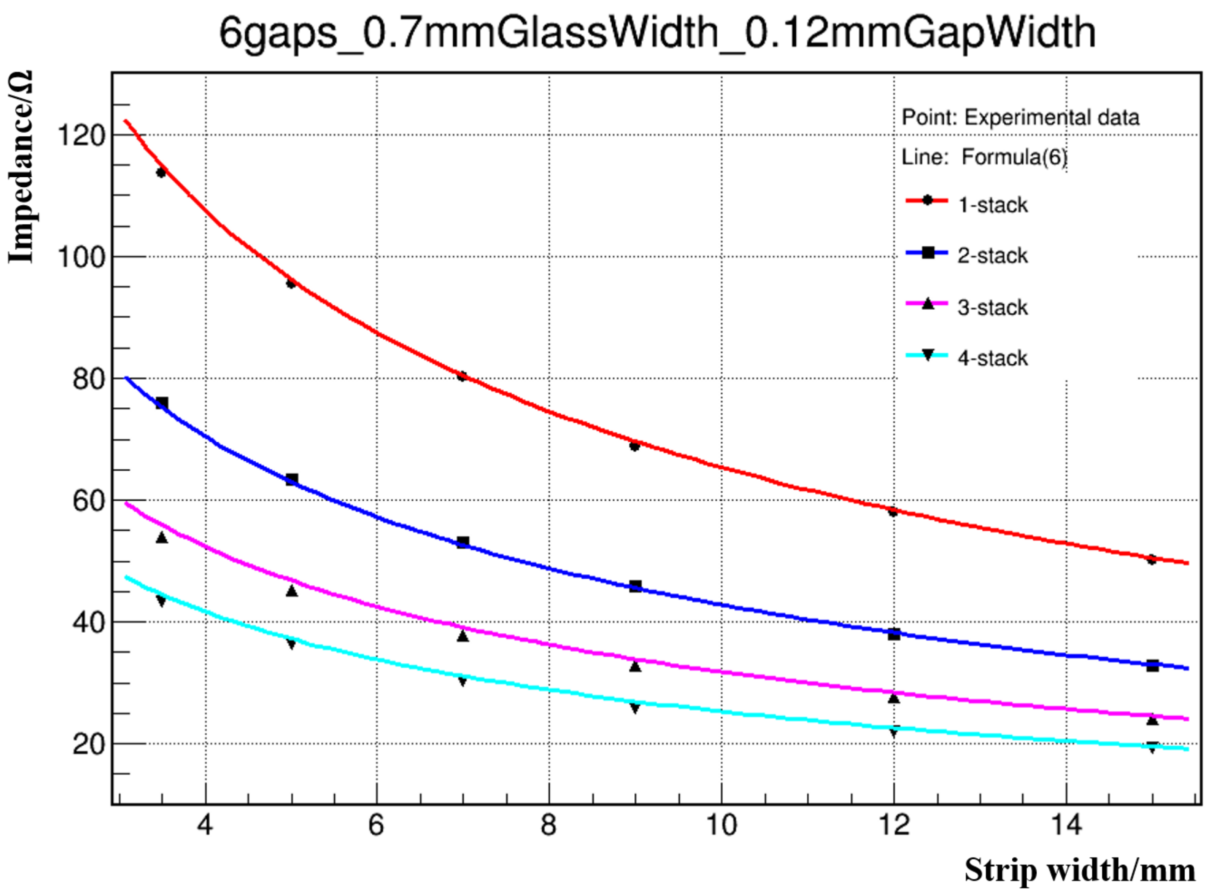
0.895 ± 0.0089

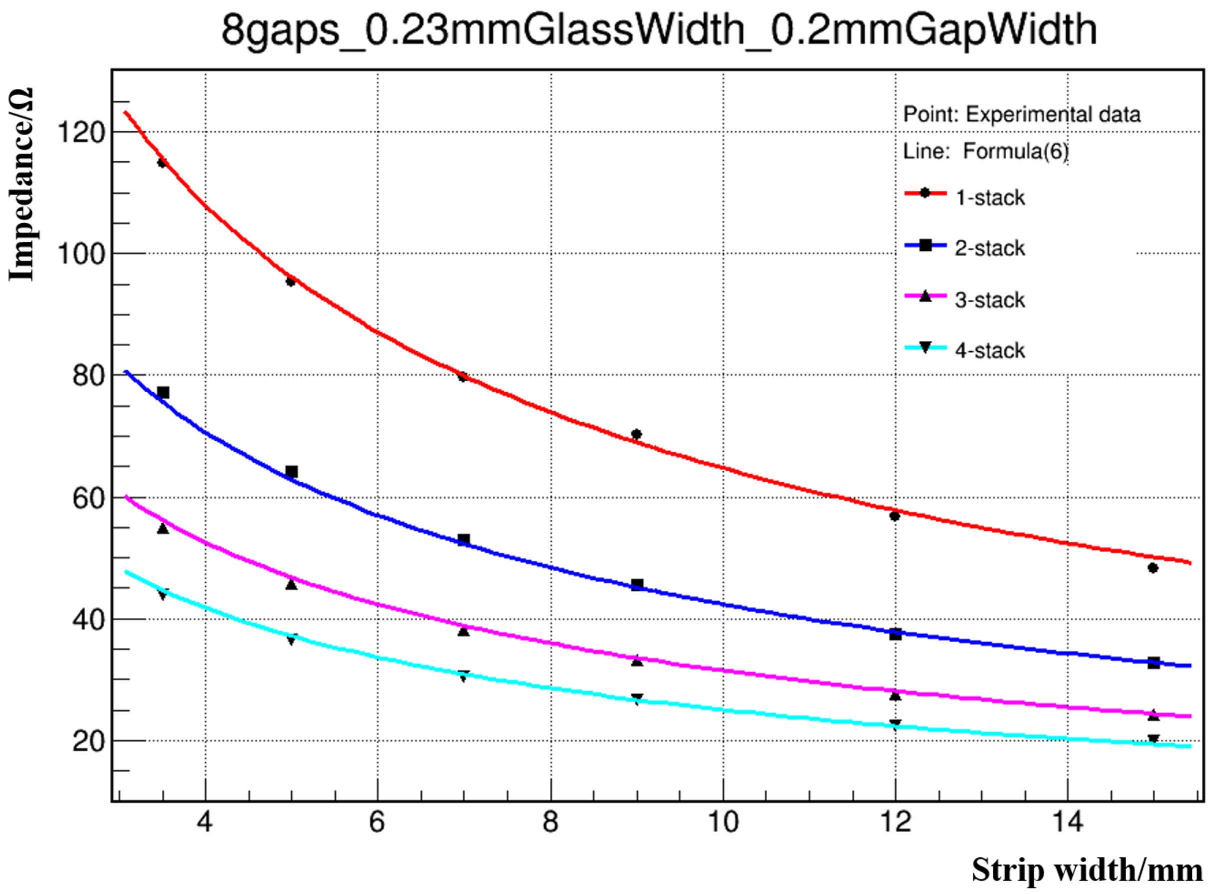
RMSE= 1.2043

R-square= 0.9977



Approximate formula for impedance estimation





Machine learning approaches--SVR

New idea:

Predict the impedance of transmission lines using machine learning approaches

✓ **Support vector machines (SVMs)** are a set of supervised learning methods used for classification, regression and outliers detection

The basic idea:

Suppose we are given training data $\{(x_1, y_1), \ldots, (x_m, y_m)\} \in R^n \times R$, where n means the dimension of input patterns.

In ε-SV regression, we begin by describing the case of linear functions f , taking the form:

$$f: R^n \to R \text{ with } f(x) = \boldsymbol{W} \cdot \boldsymbol{X} + b \text{ and } \boldsymbol{W} \in R^n, b \in R$$

We can write this problem as a convex optimization problem:

Minimize: $\frac{1}{2}\|\boldsymbol{W}\|^2$

Subject to $y_i - \boldsymbol{W} \cdot \boldsymbol{X_i} - \boldsymbol{b} \leq \boldsymbol{\varepsilon}$

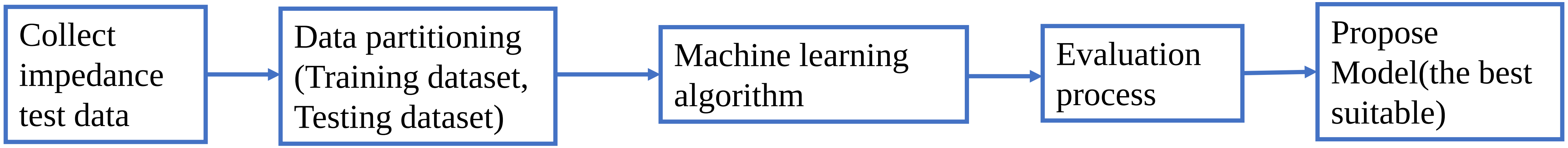
$\boldsymbol{W} \cdot \boldsymbol{X_i} - \boldsymbol{b} - y_i \leq \boldsymbol{\varepsilon}$

Machine learning approaches--SVR

class sklearn.svm.SVR (kernel='**rbf**', degree=3, gamma='auto', coef0=0.0, tol=0.001, C=1.0, epsilon=0.1, shrinking=True, cache_size=200, verbose=False, max_iter=-1)

The free parameters : the values of the cost function C, the width ε and kernel function

Workflow diagram of experiment design



numofstack	numofgaps	widthofglass	widthofgaps	widthofstrips	dielectric	Impedance
1	4	0.23	0.28	3.5	3.11	90.47
1	4	0.23	0.28	5.0	3.11	75.33
1	4	0.23	0.28	7.0	3.11	60.67
1	4	0.23	0.28	9.0	3.11	52.07
1	4	0.23	0.28	12.0	3.11	42.22
1	4	0.23	0.28	15.0	3.11	35.56
2	4	0.23	0.28	3.5	3.11	63.80
2	4	0.23	0.28	5.0	3.11	50.42
2	4	0.23	0.28	7.0	3.11	42.25
2	4	0.23	0.28	9.0	3.11	35.31
2	4	0.23	0.28	12.0	3.11	28.94
2	4	0.23	0.28	15.0	3.11	24.40
3	4	0.23	0.28	3.5	3.11	45.48
3	4	0.23	0.28	5.0	3.11	37.21
3	4	0.23	0.28	7.0	3.11	30.59

- SVR
(parameter setting, kernel type selection)

- Mean absolute error(MAE)
- Mean squared error(MSE)
- R^2 score, the coefficient of determination

Machine learning approaches--SVR

Model Attributes	Kernel type	Degree	C	Gamma	MAE	MSE	R^2 score
Number of stacks, Number of gaps, Width of glass, Width of gaps, Width of strip, Equivalent dielectric constant	'rbf'	3	500	0.06	1.254	2.315	0.996
	'rbf'	**3**	**600**	**0.07**	1.124	2.002	0.996
	'rbf'	3	500	0.08	1.188	2.222	0.996
	'rbf'	3	500	0.1	1.344	2.664	0.995
	'rbf'	3	1000	0.1	1.576	3.026	0.994
	'rbf'	3	3000	0.1	1.682	3.401	0.994
	'rbf'	3	500	0.2	2.401	7.04	0.987
	'rbf'	3	1000	0.2	2.396	7.058	0.987
	'poly'	3	1000	0.1	3.16		0.957

"rbf"(radial basis function): exp(-gamma*|u-v|^2)

Machine learning approaches--SVR

kernel='**rbf**'   C=600 Gamma=0.07

numofstack	numofgaps	thicknessofglass	thicknessofgaps	widthofstrips	dielectric	Impedance_Test	Impedance_Predict
1	5	0.23	0.28	3.5	3.1300	**101.45**	**99.40**
1	5	0.23	0.28	5.0	3.1300	**83.02**	**82.33**
1	5	0.23	0.28	7.0	3.1300	**69.76**	**67.26**
1	5	0.23	0.28	9.0	3.1300	**59.41**	**57.88**
1	5	0.23	0.28	12.0	3.1300	**48.27**	**47.11**
1	5	0.23	0.28	15.0	3.1300	**41.35**	**39.00**
1	7	0.23	0.28	3.5	3.0635	**119.53**	**117.96**
1	7	0.23	0.28	5.0	3.0635	**99.46**	**100.98**
1	7	0.23	0.28	7.0	3.0635	**84.14**	**84.08**
1	7	0.23	0.28	9.0	3.0635	**73.14**	**73.39**
1	7	0.23	0.28	12.0	3.0635	**59.80**	**60.13**
1	7	0.23	0.28	15.0	3.0635	**50.69**	**50.28**

- Mean absolute error: **1.124**
- Mean squared error: **2.002**
- R^2 score, the coefficient of determination: **0.996**

Data Analysis Methods

	Machine learning approaches--SVR	Approximate formula
Resistive electrodes	Float glass(ε=6.5)	Float glass(ε=6.5)
The number of stacks	1,2,3,4	1,2,3,4
The number of gas gaps	4 ~8	4 ~8
Width of strips	3.5~15	3.5~15
Thickness of gaps	0.12~0.28	0.1~0.3
Thickness of glass	0.23~0.7	0.23~0.7

- These two methods for impedance estimation in MRPC detector show a good performance under the condition shown in the table above

Conclusion

- A 6-gap MRPC prototype has been developed
  - ✓ Time resolution can reach 35ps at ±9100V
- An approximate formula for calculating the impedance of transmission lines in MRPC Detector has been proposed.

$$\boldsymbol{Imp} = \frac{\frac{\boldsymbol{a(1)}}{\sqrt{\boldsymbol{\varepsilon + a(2)}}} \times \boldsymbol{log}\frac{\boldsymbol{a(3) \times n \times w2 + a(4) \times (n+1) \times w1}}{\boldsymbol{w - a(5)}} + \boldsymbol{a(6)} \times \sqrt{\frac{\boldsymbol{w}}{\boldsymbol{n \times w2 + (n+1) \times w1}}} + \boldsymbol{a(7)} \times \boldsymbol{log}\frac{\boldsymbol{w1}}{\boldsymbol{w2}}}{\boldsymbol{ns + a(8)}}$$

- Predict the impedance of transmission lines using machine learning approaches----SVR(Support Vector Regression)

Thank you for your attention!